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# Discovery of a bow shock around Vela X–1

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## ABSTRACT

We report the discovery of a symmetric bow shock around the well-known high-mass X-ray binary (HMXB) Vela X–1. Wind bow shocks are a ubiquitous phenomenon around OB-runaway stars, but now such a structure is found around a HMXB. The presence of a bow shock indicates that the system has a high (supersonic) velocity with respect to the interstellar medium. From the symmetry of the bow shock, the direction of motion and, moreover, the origin and age of the system can be derived. Our observation supports Blaauw's scenario for the formation of an OB-runaway star by the supernova explosion of the binary companion.

*Subject headings:* Stars: binaries: close – stars: individual: HD77581 – stars: mass-loss – pulsars: individual: Vela X–1 – supernovae: general – open clusters and associations: individual: Vel OB1

## 1. Introduction

The high-mass X-ray binary (HMXB) HD77581 (Vela X-1) consists of a B0.5 Ib supergiant (Vidal et al. 1973, Jones & Liller 1973) and an X-ray pulsar companion ($P_{\rm pulse}$=283s, McClintock et al. 1976) in an 8.9 days orbit. Pulse-timing analysis of the X-ray pulsar has resulted in the accurate determination of its orbital parameters (Nagase 1989). The length of the X-ray eclipses (Watson & Griffiths 1977) indicates that the inclination of the orbital plane is close to 90°. Also the radial-velocity curve of the supergiant companion is measured (Van Paradijs et al. 1977, Van Kerkwijk et al. 1995a), so that the masses of both binary components ($23.5^{+2.2}_{-1.5}$ and $1.88^{+0.69}_{-0.47}$ $M_\odot$, $3\sigma$ limits) can be derived. It turns out that Vela X–1 is the most massive neutron star known (Van Kerkwijk et al. 1995b), although the $3\sigma$ error bar still includes the canonical neutron star mass of 1.4 $M_\odot$.

Evolutionary scenarios for massive binaries (see e.g. Van den Heuvel 1993 for a review) predict that the HMXB Vela X–1 originates from a 25+22.5 $M_\odot$ binary (cf. Van Rensbergen et al. 1996). When the initially most massive star (the primary) becomes a supergiant and starts filling its Roche lobe, a phase of mass transfer occurs, rejuvenating the secondary that eventually becomes the most massive star in the system. The primary evolves into a helium star that leaves a neutron star (or a black hole) after a supernova explosion. When less than half of the total mass of the system is lost, the system (now containing an OB star and a compact companion) remains bound (Blaauw 1961) and gets a kick velocity. The binary system then leaves the location where it was born. As soon as the secondary OB star evolves into a supergiant, accretion of its dense stellar wind onto the compact star will power a strong X-ray source. Thus, according to this model of massive binary evolution, all HMXBs should be runaways.

### 1.1. Blaauw's scenario

Zwicky (1957) and Blaauw (1961) were the first to realize that a supernova explosion of one of the binary components can result in a high space velocity of the companion star. This mechanism for the formation of OB-runaway stars is presently known as Blaauw's scenario. In the original scenario a phase of mass transfer was not included, so that the massive binary had a higher probability to disrupt after the supernova explosion of the primary. But the modern version of this scenario predicts that the resulting runaway star has a high probability to remain bound to its compact companion (Van den Heuvel 1993, Hills 1983). Although many people expect that a significant fraction of OB runaways has a compact companion, searches for compact stars around OB runaways have up to now not been successful (e.g. Philp et al. 1996).

As a result of a phase of mass transfer in a compact binary, one might expect that the abundances of nuclear processed elements are enhanced in the atmosphere of an OB-runaway star. Also, the angular momentum associated with the accreted material will increase the rotation rate of the OB runaway. For a small sample of bright OB runaways, Blaauw (1993) shows that these stars indeed exhibit a tendency towards higher helium abundance and higher projected rotational velocity. He further argues that some OB runaways seem to be younger than the age of the OB association they originate from (these stars are called blue stragglers). These observations provide, however, only circumstantial evidence for the supernova origin of (some) OB runaways.

### 1.2. Cluster ejection mechanism

An alternative explanation for the existence of OB-runaway stars is the cluster ejection model (Poveda et al. 1967): dynamical interaction in a compact cluster of stars results in

the ejection of one or more of the members. From their extensive radial velocity survey of bright OB-runaway stars, Gies & Bolton (1986) concluded that the cluster ejection model should be favoured. Their conclusion is mainly based on arguments refuting a supernova origin for the observed OB-runaway stars. Apart from the lack of observational evidence for the presence of compact companions around OB runaways, the existence of 2 runaway double-lined spectroscopic binaries cannot be explained with the supernova model. Also the kinematical age of OB-runaway stars (i.e. the time needed to reach its present position with respect to the "parent" OB association) is often close to the age of the OB association itself, which is in support of the cluster ejection model. On the basis of the observed radial velocities they argued that the population of HMXBs and OB-runaways appears to be different. Van Oijen (1989), however, found strong indications that HMXBs are high velocity objects.

In the following we will provide compelling observational evidence that at least one HMXB is an OB runaway system, that obtained its high space velocity through the supernova explosion of the compact star's progenitor.

## 2. Wind bow shock around Vela X–1

Kinematic studies of OB stars are hampered by the large distances at which these stars are usually found, making it very difficult to measure proper motions accurately (although this situation will be significantly improved after release of the Hipparcos data). But it turns out that many OB stars with high space velocity create an unmistakable sign in the surrounding space. When an OB star moves supersonically through the interstellar medium (ISM), the interaction of its stellar wind with the ISM gives rise to a bow shock. Van Buren & McCray (1988) examined the Infra Red Astronomical Satellite (IRAS) all-sky survey at the location of several OB-runaway stars and found extended arc-like structures associated

with many of them. The infrared emission results from interstellar dust that is swept up by the bow shock and heated by the radiation field of the OB star. In a subsequent study (Van Buren et al. 1995), wind bow shocks were detected around one-third of a sample of 188 candidate OB-runaway stars. Thus, the detection of a wind bow shock can be considered as an observational confirmation of the runaway status of an OB star.

To this aim, we searched for the presence of a wind bow shock around the HMXB Vela X–1. This is a good candidate for an OB runaway system. Its runaway nature was proposed in a recent paper by Van Rensbergen et al. (1996), based on the observed annual proper motion of HD77581 listed in the Hipparcos Input Catalogue (Turon et al. 1992, see Table 1). The direction of the annual proper motion suggests that HD77581 might originate from the OB association Vel OB1, which is located at a distance of 1820 parsec (Humphreys 1978) from the Sun. At that distance, HD77581 (Vela X–1) would have a space velocity of about 90 km $s^{-1}$ and would have left Vel OB1 $2 \pm 1$ million years ago. They further showed that this kinematical age is consistent with the predicted time of supernova explosion of Vela X-1's progenitor.

Figure 1 (Plate X) shows a narrow-band H$\alpha$ image of a $10 \times 10$ arcminute-squared field centered on Vela X–1, obtained with the 1.54m Danish telescope at the European Southern Observatory (ESO) on February 14, 1996. The bright star HD77581 (V=6.9) has been removed (including its reflections) from the H$\alpha$ frame (exposure time 20 minutes) by subtracting a properly scaled R-band image of the same field. The uncalibrated H$\alpha$ image clearly reveals the presence of a bow shock, the apex being at $0.9 \pm 0.1$ arcminute to the north of HD77581. At the distance of HD77581 (see below), this corresponds to a projected distance of $0.48 \pm 0.05$ parsec. With help of the flux-calibrated long-slit spectrum (see Fig. 2) and knowledge of the position and dimensions of the slit, we estimate (within a factor of two) the image peak H$\alpha$ intensity to be $\sim 10^{-15}$ erg $s^{-1}$ $cm^{-2}$ $arcsec^{-2}$. The

western (right) part of the bow shock consists of two separate filaments. Obviously, one filament is the continuation of the bow shock to the west. Filamentary structure has been observed in other wind bow shocks as well and might be related to their instability (Dgani et al. 1996). The IRAS small-scale structure catalogue (Helou & Walker 1988) lists an extended infrared source at the position of Vela X–1. The extended source can be identified as an H II region with a Strömgren radius of $\sim 0.2$ degrees ($\sim 7$ parsec). We produced a high-resolution IRAS map (not shown here) of this area on the sky and found that inside the H II region the bow shock is well resolved at infrared wavelengths too, most pronounced in the 60$\mu$m wavelength band.

## 3. Bow shock structure

The structure of a wind bow shock is determined by the balance between the ram pressures of the wind and the ambient medium (Baranov et al. 1971). One can show that:

$$4\pi\rho_a v_\star^2 R_0^2 = \dot{\mathrm{M}}_w v_w \, .$$

Using the observed value for the distance $R_0$ between the OB star and the stagnation point (apex), the mass-loss rate $\dot{\mathrm{M}}_w = 10^{-6}$ $\mathrm{M}_\odot$ yr$^{-1}$ and terminal velocity $v_w = 1105$ km s$^{-1}$ of the stellar wind of HD77581 (Kaper et al. 1993), and 90 km s$^{-1}$ for the space velocity $v_\star$ of the system, we derive for the density of the ambient medium: $\rho_a \approx 2.6 \times 10^{-24}$ g cm$^{-3}$ (number density $\sim 1$ cm$^{-3}$).

A rough estimate of the local ISM density can be obtained from the size of the H II region and also from its observed infrared flux. Following Osterbrock (1989) and assuming that the H II region is a pure hydrogen nebula, optically thick in the Lyman series, a Strömgren radius of 7 parsec and a black-body input spectrum ($T_{\mathrm{eff}}$=20.000 K) results in a neutral hydrogen number density $n_{\mathrm{H}}$ of 6 cm$^{-3}$. The total IR flux produced by dust inside

the H II region is a measure for the number of Ly$\alpha$ photons produced by recombinations. The flux observed by IRAS (integrated over the H II region and corrected for the IRAS band widths) is $3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. A black-body fit to the flux values shows that the dust temperature is 78 K and that the total dust emission is $5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, about 1.7 times the flux detected by IRAS. The energy per second per unit volume produced by recombination to the ground level is $3.3 \times 10^{-24} \times n_{\rm H}^2$ erg cm$^{-3}$ s$^{-1}$. Comparison with the measured IR flux gives $n_{\rm H} = 16$ cm$^{-2}$. If the emission from the bow shock is excluded, this yields $n_{\rm H} = 11$ cm$^{-2}$. Given the uncertainties, the estimate of the local ISM density with help of the bow shock and stellar wind parameters is probably the most accurate.

We obtained a long-slit spectrum of the bow shock with the ESO 1.52m telescope on the night of May 28, 1995 (Figure 2). We show a flux-calibrated spectrum for two regions covered by the slit; the orientation and position of the slit is indicated in the sub-panel. The spectra include the H$\alpha$ and H$\beta$ lines, and forbidden emission lines like [O III] $\lambda\lambda$4959,5007 Å and [N II] $\lambda$6583 Å. Region A corresponds to the secondary filament which appears to produce the maximum H$\alpha$ intensity. The H$\alpha$/H$\beta$ ratio in region A is 6.5; if this large ratio is due to extinction, E(B-V) would be equal to 0.72, which is consistent with the reddening of HD77581 (Sadakane et al. 1985). In region B, which covers a part of the wind bow shock, the Balmer lines are much weaker with respect to the forbidden [O III] lines ([O III] $\lambda$5007/H$\beta \geq 4.1$) than in region A ($\approx 1.5$). Compared to other usual shock-excited emission lines, the [O III] lines originate close to the shockfront where the ionization conditions depend critically on shock conditions (Dopita 1977, Hollis et al. 1992). Therefore, the spectra are in accordance with both regions being part of the wind bow shock. The filament covered by region A might be experiencing a somewhat weaker shock, yielding a much larger emission measure in H$\alpha$.

## 4. Discussion and conclusions

The present position of HD77581 and the OB association Vel OB1 is shown in Figure 3. The separation between the two is about 7 degrees. The direction of the proper motion of HD77581, (a) as listed in the HIC and (b) as measured by Sahu (1992), is indicated. The dotted line represents the proposed path of HD77581 based on the symmetry-axis of the bow shock, which is in a direction in between the proper motion vectors $\vec{a}$ and $\vec{b}$. The bow shock reflects the relative motion between the star and the surrounding medium, while the proper motion measures the star's motion with respect to other stars. Since the gas has a 10 km s$^{-1}$ dispersion, $5-10^{\circ}$ deviations can be expected, which would favour $\vec{b}$. If the proposed path is correct, the origin of the binary system would be on the outskirts of Vel OB1. The usually adopted distance towards Vela X–1 of $1.9 \pm 0.1$ kpc (Sadakane et al. 1985) is in accordance with the stellar parameters of HD77581. The accretion induced X-ray luminosity of Vela X–1 (Kaper et al. 1993), also agrees very well with the distance towards Vel OB1. Thus, our observations confirm the proposed runaway status of HD77581 and support its suggested origin in Vel OB1.

In conclusion, the discovered wind bow shock around Vela X–1 provides compelling observational evidence for a runaway high-mass X-ray binary. The direction of motion of the system is derived from the symmetry of the bow shock and it is very likely that the OB association Vel OB1 is the origin of the system. From the observed proper motion one can compute that the system left the outskirts of Vel OB1 about 2.5 million years ago, which corresponds to the expected time of the supernova explosion of Vela X-1's progenitor. Therefore, our observations support Blaauw's scenario for the formation of the runaway high-mass X-ray binary HD77581 (Vela X–1). It remains to be shown whether all HMXBs are runaway systems. We predict that the answer to this question is positive and expect that in at least a third of the cases a wind bow shock is associated with them.

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Table 1: Proper motion, radial velocity, and space velocity of HD77581 at the distance (1820 parsec) of Vel OB1; for the space velocity, the average radial velocity of the OB stars in Vel OB1 (26.7 km $s^{-1}$, Humphreys, 1978) is taken into account. $\star$: radial velocity taken from Gies & Bolton (1986).

| | $\mu_\alpha \cos\delta$ (”/yr) | $\mu_\delta$ (”/yr) | $v_r$ (km $s^{-1}$) | $v_\star$ (km $s^{-1}$) |
|---|---|---|---|---|
| (a) Turon et al. 1992 | +0.004(3) | +0.009(3) | $-1$ | 89(40) |
| (b) Sahu 1992 | -0.0014(19) | +0.0107(22) | $-4^\star$ | 98(26) |

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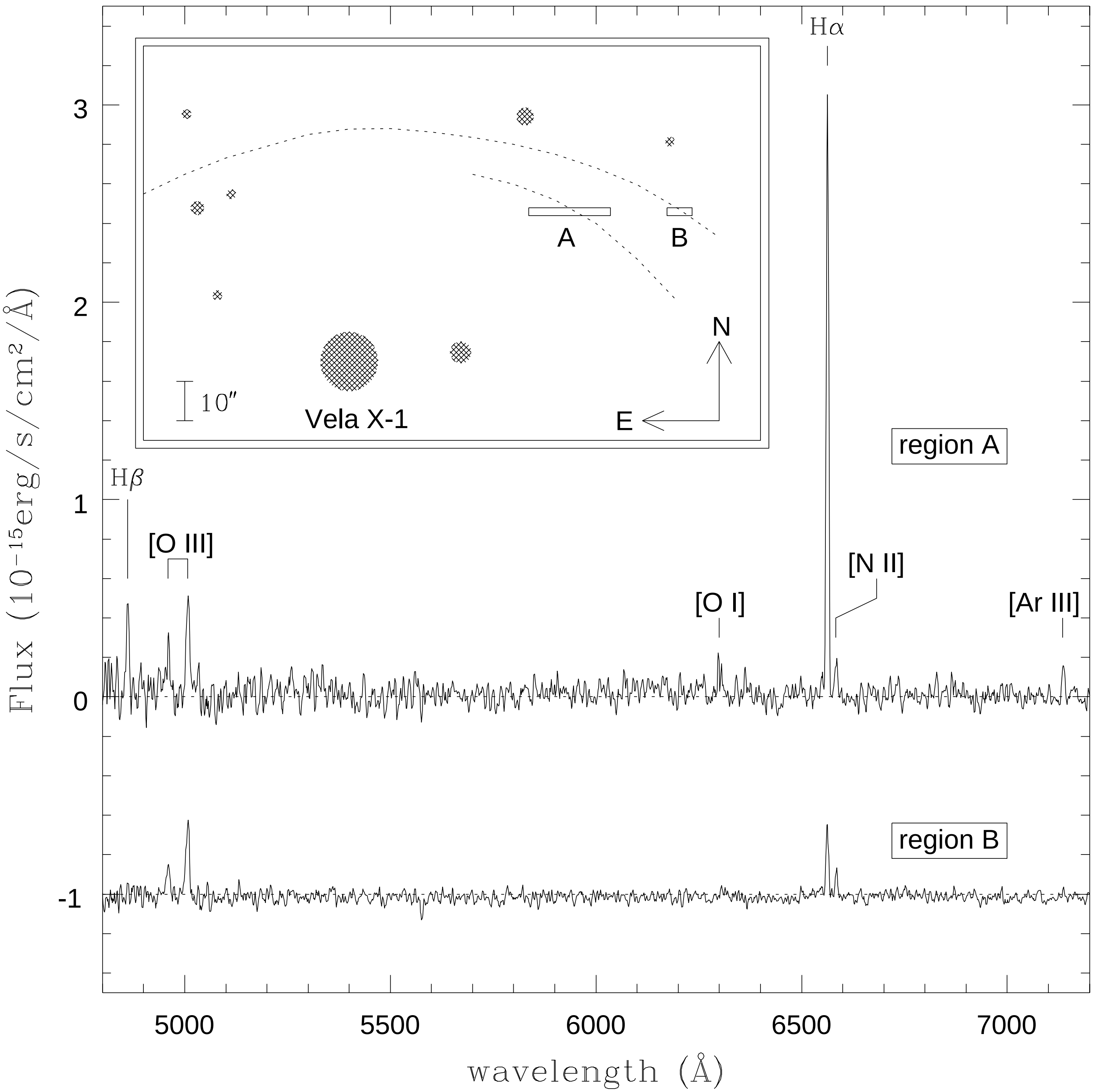
*Fig. 1:* (Plate X): An R-band corrected H$\alpha$ image of the field around Vela X–1 is shown. North is up and east to the left. The images were obtained with the DFOSC instrument and a CCD detector in the Cassegrain focus of the 1.54m Danish telescope at the European Southern Observatory. A wind bow shock is detected about 0.9 arcminute north of the (saturated) 6$^{\rm th}$ magnitude star HD77581. The western (right) arm of the bow shock is split into two filaments, a feature more often encountered in wind bow shocks.

*Fig. 2:* A flux-calibrated long-slit spectrum of the bow shock was obtained with the Boller & Chivens spectrograph mounted on the 1.52m ESO telescope. The spectrum was collapsed in the spatial direction along two regions in the slit (length 4.2 arcminutes) which are shown in the sub panel. The spectral resolution is 5.5 Å (FWHM). Region A corresponds to the secondary filament which appears to produce the maximum H$\alpha$ intensity. Region B is the extension of the wind bow shock to the west. The forbidden [O III] lines are indicative of shock excitation.

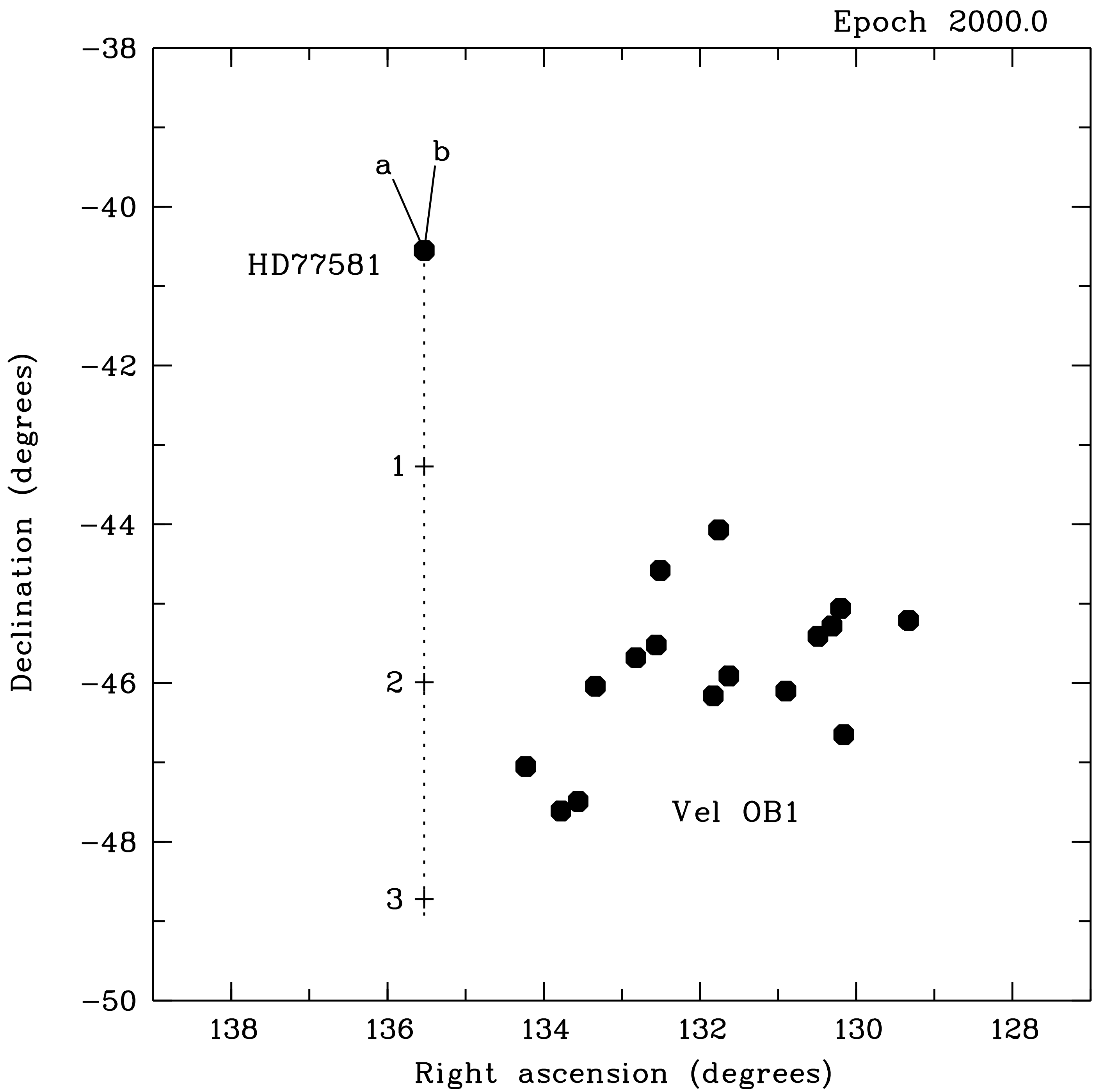
*Fig. 3:* The position of HD77581 (Vela X–1) on the sky with respect to the OB association Vel OB1. Right ascension and declination are given in degrees, north is up and east to the left. The direction of proper motion, listed in the HIC ($\vec{a}$) and obtained by Sahu (1992) ($\vec{b}$), is shown. The proposed path of the system, based on the symmetry axis of the bow shock, is given by a dotted line. The numbers along this line indicate the position where the system would have been (respectively 1,2, and 3 million years ago), given a velocity of 90 km s$^{-1}$.

This figure "bowshockcont.gif" is available in "gif" format from:

http://arXiv.org/ps/astro-ph/9611017v1



Hα
region A
region B
Hβ
[O III]
[O I]
[N II]
[Ar III]
A
B
N
E
10″
Vela X-1
Flux (10^-15 erg/s/cm^2/Å)
wavelength (Å)
3
2
1
0
-1
5000
5500
6000
6500
7000


Epoch 2000.0
HD77581
a
b
1
2
3
Vel OB1
Declination (degrees)
Right ascension (degrees)
−38
−40
−42
−44
−46
−48
−50
138
136
134
132
130
128